International Journal of Mechanics and Energy (IJME)
Vol. 5, Issue 1, 2017, ISSN: 2286-5845

Modeling and simulation of a solar cooker with box type

Zied Guidara*[,1], Mahamoud Souissi[1,2], Alexander Morgenstem[3], Aref Maalej[1]

[1] *Laboratory of Electro-Mechanic Systems (LASEM), National School of Engineers of Sfax (ENIS), University of Sfax (US),*
B.P. 1173, Road Soukra km 3.5, 3038 Sfax, TUNISIA

[2] *National School of Engineers of Sousse (ENISo), Sousse Technological Pole, University of Sousse*
B.P. 264, Erriadh, 4023 Sousse, TUNISIA

[3] *Division of Thermal Systems and Buildings, Fraunhofer Institutfür Solare Energie systeme ISE Heidenhofstraße 2,*
79110 Freiburg, GERMANY

Abstract: In this paper, the design of a box type solar cookeris presented first. The main components of this solar cooker are inner and outer reflectors, a double glazing, an absorber plate and a cooking box. Secondly, in order to predict the evolution of the temperatures of the main components of the solar cooker,a mathematical model was developed and implemented in a MATLAB program using finite differences method. To validate the accuracy of the calculations further numerical simulations were realized using Solidworks simulation tool. After that, simulations were developed on the solar cooker before enhancement and after enhancement with four outer reflectors. The obtained results show that the enhancement has a great influence on the maximum temperature of each component and on the availability of the solar cooker.

Keywords: Design, box type solar cooker, mathematical model, numerical simulations, reflectors.

1. Introduction

Different types of solar cookers have been the focus of many studies. However, reducing the baking time still present a huge challenge for this technology to thrive and to be commercialized in a wide range.

To overcome this problem, many researches have proposed to modify baking tools form to increase the food heat exchange through the walls of the baking tools. In this context, Gaur et al. [1], proposed a baking tool with a concave cover to increase the effective heat exchange surface. Experiments realized on this baking tool have shown a decrease of the baking time by 10 to 13 % compared to baking time done with an ordinary tool in the same operating conditions. To better the heat exchange between the inner air in the cooker and the baking tool, Narashima et al. [2] used a baking tool with a central cavity.

Experiments have shown that this configuration increases the heat exchange surface and consequently the baking time. Although these ameliorations have improved the baking time, they presented the disadvantage of reducing the space dedicated to the food to be cooked.Harmim et al. [3], proposed a new form of baking tool which consists on an ordinary cylindrical container with fins on its outer wall. This configuration has considerably reduced the baking time. Although this configuration reduces the baking time and permits a satisfactory space for food, the manufacturing of such container would be too expensive.Another way to enhance the baking time is to maximize the solar radiation collection. Many researches were realized and many designs were proposed in this context namely box type solar

---

***Corresponding author:** Zied Guidara
E-mail: ziedguidara@yahoo.fr.

cookers [4], concentrator type solar cookers [5] and oval type solar cookers [6]. However, box type solar cookers are the most suitable for domestic use owing to their simple construction.

In this paper, a full description of the design of a box type solar cooker is proposed, a theoretical study and a mathematical modeling are also provided. After that, a numerical simulation is conducted to verify the consistence of the model. Finally, the main conclusion of this work is presented.

2. Description of the solar cooker

The proposed solar cooker is destined to operate in a Mediterranean climate. When designing, these conditions must be took into consideration:

- Easy manufacturing,
- Available manufacturing materials in local market,
- Easy exploitation of the device during the whole year.

The proposed solar cooker is a box type. It is mainly composed of a wood box, an horizontal black body (an absorber plate), an inner reflector, and four outer reflectors.Fig. 1shows the design of the solar cooker subject of study.

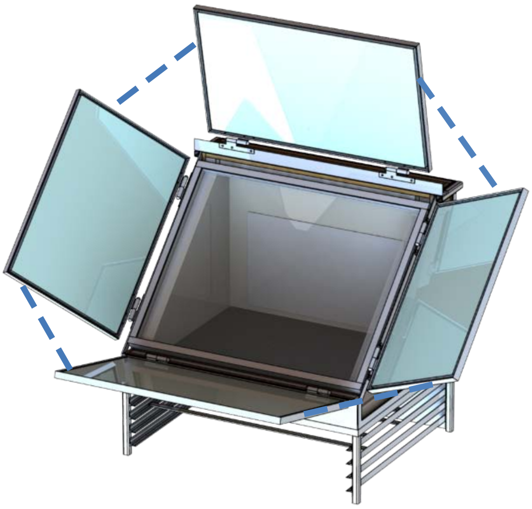


Fig. 1 Design of the solar cooker

The black body placed at the base of the wood box is constituted of an aluminum plate which is painted in black. This aluminum plate absorbs the solar radiation that is transmitted by an inclined double glass panel and a vertical reflector which is placed on the inner back of the box. To maximize the solar radiation capture, four reflectors with adjustable tilt angle reflect an additional amount of solar radiation over the glass panel. The heat transfer between the aluminum plate and the container (not represented) is done by conduction while it is done with convection between air and the container walls.

Table 1provides the main geometrical parameters values of the solar cooker.

Table 1 Main geometric parameters of the solar cooker

Parameter	Value	Unit
Outer reflectors total surface area	0.4279	m^2
Inner reflector surface area	0.1460	m^2
Effective glass surface	0.3654	m^2
Aluminum plate surface area	0.2872	m^2
Air gap mean thickness	0.2375	m

3. Modeling of the solar cooker

The adopted model is implemented on a MATLAB program to carry out the temperatures of the different components of the solar cooker during one day. Simulations are realized on a vacant box (i.e. without container in it). The evolution of the aluminum plate allows to determine the average baking time; the higher is the temperature and the shortest is the baking time.

The main elements constituting the model to be simulated are:

- Ambient air,
- The double glass panel,
- The inner air,
- The inner reflector,
- The outer reflectors,
- The black painted aluminum plate.

To facilitate the calculations, the following assumptions are adopted:

- The components temperatures are uniform.
- Only the double glass panel and the aluminum plate are supposed to absorb solar radiation.
- Physical and thermal properties of the different components are constant in the operating temperature range.

The ambient conditions under which the model is simulated are provided in Fig. 2.

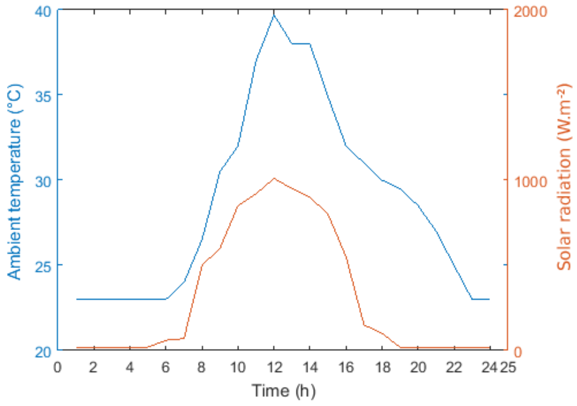


Fig. 2 Ambient condtions: Ambient temperature / Solar radiation

To put in evidence the influence of the four outer reflectors on the components temperatures, the model is simulated at first only with the inner reflector, then with four outer reflectors at a preset tilt angles.

3.1. Energy balance equations of the solar cooker without outer reflectors

The energy balance equation of the first glass is given by the following expression:

$$\{\dot{Q}_{ab,G1}\} + \{\dot{Q}_{cv,G2,G1}\} + \{\dot{Q}_{r,G2,G1}\} \\ = \{\dot{Q}_{acc,G1}\} + \{\dot{Q}_{cv,G1,amb}\} + \{\dot{Q}_{r,G1,s}\} \qquad (1)$$

where $\{\dot{Q}_{ab,G1}\}$ is the absorbed solar radiation, $\{\dot{Q}_{cv,G2,G1}\}$ is the convective heat rate between the first glass and the second glass, $\{\dot{Q}_{r,G2,G1}\}$ is the second glass radiation heat rate over the first glass, $\{\dot{Q}_{acc,G1}\}$ is the accumulation heat rate of the first glass, $\{\dot{Q}_{cv,G1,amb}\}$ is the convective heat rate between the first glass and the ambient air, and $\{\dot{Q}_{r,G1,s}\}$ is the first glass radiation heat rate over the sky.

These heat rates expressions can be written as follows:

$$\{\dot{Q}_{ab,G1}\} = \alpha_{G1} S_{G1}\, I \qquad (2)$$

$$\{\dot{Q}_{cv,G2,G1}\} = h_{cv,G2,G1} S_{G1} (T_{G2} - T_{G1}) \qquad (3)$$

$$\{\dot{Q}_{r,G2,G1}\} = h_{r,G2,G1} S_{G1} (T_{G2} - T_{G1}) \qquad (4)$$

$$\{\dot{Q}_{acc,G1}\} = m_{G1} C_{pG} \frac{dT_{G1}}{dt} \qquad (5)$$

$$\{\dot{Q}_{cv,G1,amb}\} = h_{cv,G1,amb} S_{G1} (T_{G1} - T_{amb}) \qquad (6)$$

$$\{\dot{Q}_{r,G1,s}\} = h_{r,G1,s} S_{G1} (T_{G1} - T_s) \qquad (7)$$

where α_{G1} is the absorption coefficient of the glass, S_{G1} is the effective glass surface, I is the solar radiation, h is the heat transfer coefficient, m is the mass, C_p is the specific heat capacity, and T is the temperature of the component.

The temperature of the sky can be expressed as[7]:

$$T_s = 0.0552\, T_{amb}^{1.5} \qquad (8)$$

The energy balance of the second glass is given by the following expression:

$$\{\dot{Q}_{ab,G2}\} + \{\dot{Q}_{cv,air,G2}\} + \{\dot{Q}_{r,p,G2}\} \\ = \{\dot{Q}_{acc,G2}\} + \{\dot{Q}_{cv,G2,G1}\} + \{\dot{Q}_{r,G2,G1}\} \qquad (9)$$

where $\{\dot{Q}_{ab,G2}\}$ is the absorbed solar radiation, $\{\dot{Q}_{r,p,G2}\}$ is the black aluminum plate radiation rate over the second glass, $\{\dot{Q}_{acc,G2}\}$ is the accumulation heat rate in the second glass, $\{\dot{Q}_{cv,air,G2}\}$ is the convective heat rate between the inner air gap and the second glass. The previous heat rates are expressed as:

$$\{\dot{Q}_{ab,G2}\} = \alpha_{G2}\, \tau\, S_{G2}\, I \qquad (10)$$

$$\{\dot{Q}_{r,p,G2}\} = h_{r,p,G2} S_{G2} (T_p - T_{G2}) \qquad (11)$$

$$\{\dot{Q}_{acc,G2}\} = m_{G2} C_{pG} \frac{dT_{G2}}{dt} \qquad (12)$$

$$\{\dot{Q}_{cv,air,G2}\} = h_{cv,air,G2} S_{G2} (T_{G2} - T_{air}) \qquad (13)$$

where τ is the coefficient of transmission of the glass.
The air gap energy balance can be written as follows:

$$\{\dot{Q}_{cv,p,air}\} = \{\dot{Q}_{acc,air}\} + \{\dot{Q}_{cv,air,G2}\} \tag{14}$$

where $\{\dot{Q}_{cv,p,air}\}$ is the convective heat rate between the black aluminum plate and the air gap, and $\{\dot{Q}_{acc,air}\}$ is the air gap heat accumulation rate. The expressions of the previous heat rates are calculated using the following expressions:

$$\{\dot{Q}_{cv,p,air}\} = h_{cv,p,air}\, S_p \left(T_p - T_{air}\right) \tag{15}$$

$$\{\dot{Q}_{acc,air}\} = m_{air}\, C_{pair}\, \frac{dT_{air}}{dt} \tag{16}$$

The aluminum plate energy balance is expressed by:

$$\begin{aligned}&\{\dot{Q}_{ab,p}\} + \{\dot{Q}_{in,ref,p}\} \\ &= \{\dot{Q}_{acc,p}\} + \{\dot{Q}_{cv,p,air}\} + \{\dot{Q}_{r,p,G2}\}\end{aligned} \tag{17}$$

where $\{\dot{Q}_{ab,p}\}$ is the absorbed solar radiation by the black aluminum plate, $\{\dot{Q}_{in,ref,p}\}$ is the reflected solar radiation absorbed by the aluminum plate, and $\{\dot{Q}_{acc,p}\}$ is the aluminum plate heat accumulation rate.

The previous heat rates can be calculated using the next expressions:

$$\{\dot{Q}_{ab,p}\} = \alpha_p \tau^2 S_p\, I \tag{18}$$

$$\{\dot{Q}_{in,ref,p)}\} = \alpha_p \tau^2 S_{in,ref}\, I \tag{19}$$

$$\{\dot{Q}_{acc,p}\} = m_p\, C_{pp}\, \frac{dT_p}{dt} \tag{20}$$

3.2. Energy balance equations of the solar cooker with four outer reflectors

The use of outer reflectors provides the black aluminum plate with an additional amount of solar radiation which effects the energy balance equations of the previously cited components. Assuming that all of the reflected solar radiation which passes through the glass panel is collected by the aluminum plate, and that the four outer reflectors have the same reflecting area, the energy balance equations (1), (9) and (17) become:

$$\begin{aligned}&\{\dot{Q}_{ab,G1}\} + \{\dot{Q}_{ref,G1}\} + \{\dot{Q}_{cv,G2,G1}\} + \{\dot{Q}_{r,G2,G1}\} \\ &= \{\dot{Q}_{acc,G1}\} + \{\dot{Q}_{cv,G1,amb}\} + \{\dot{Q}_{r,G1,s}\}\end{aligned} \tag{21}$$

$$\begin{aligned}&\{\dot{Q}_{ab,G2}\} + \{\dot{Q}_{ref,G2}\} + \{\dot{Q}_{cv,air,G2}\} + \{\dot{Q}_{r,p,G2}\} \\ &= \{\dot{Q}_{acc,G2}\} + \{\dot{Q}_{cv,G2,G1}\} + \{\dot{Q}_{r,G2,G1}\}\end{aligned} \tag{22}$$

$$\begin{aligned}&\{\dot{Q}_{ab,p}\} + \{\dot{Q}_{ref,p}\} + \{\dot{Q}_{in,ref,p}\} \\ &= \{\dot{Q}_{acc,p}\} + \{\dot{Q}_{cv,p,air}\} + \{\dot{Q}_{r,p,G2}\}\end{aligned} \tag{23}$$

where $\{\dot{Q}_{ref,G1}\}$, $\{\dot{Q}_{ref,G2}\}$ and $\{\dot{Q}_{ref,p}\}$ are the additional heat rates received respectively by the fist glass, the second glass and the black aluminum plate. The expressions of these heat rates are respectively:

$$\{\dot{Q}_{ref,G1}\} = 4\, \alpha_{G1} S_{ref}\, I \tag{24}$$

$$\{\dot{Q}_{ref,G2}\} = 4\, \alpha_{G2}\, \tau\, S_{ref}\, I \tag{25}$$

$$\{\dot{Q}_{ref,p}\} = 4\, \alpha_p \tau^2\, S_{ref}\, I \tag{26}$$

3.3. Convective heat transfer coefficients

The convective heat transfer coefficient between the aluminum plate and the air gap is given by the following expression:

$$h_{cv,p,air} = 1.32\, \left(\frac{T_p - T_{air}}{L}\right)^{1/4} \tag{27}$$

Where T_p is the aluminum plate temperature, T_{air} is the air gap temperature, and L is the length of the aluminum plate.
The convective heat transfer coefficient between the air gap and the second glass can be expressed as:

$$h_{cv,air,G2} = 0.1291\, Ra^{0.304}\, \frac{\lambda_{air}}{t_{air}} \tag{28}$$

where Ra is the Rayleigh number, λ_{air} is the air gap conductivity, and t_{air} is the mean air gap thickness.
The convective heat transfer coefficient between the first glass and the ambient air is expressed as follows:

$$h_{cv,G1,amb} = 5.67 + 3.86\, V \tag{29}$$

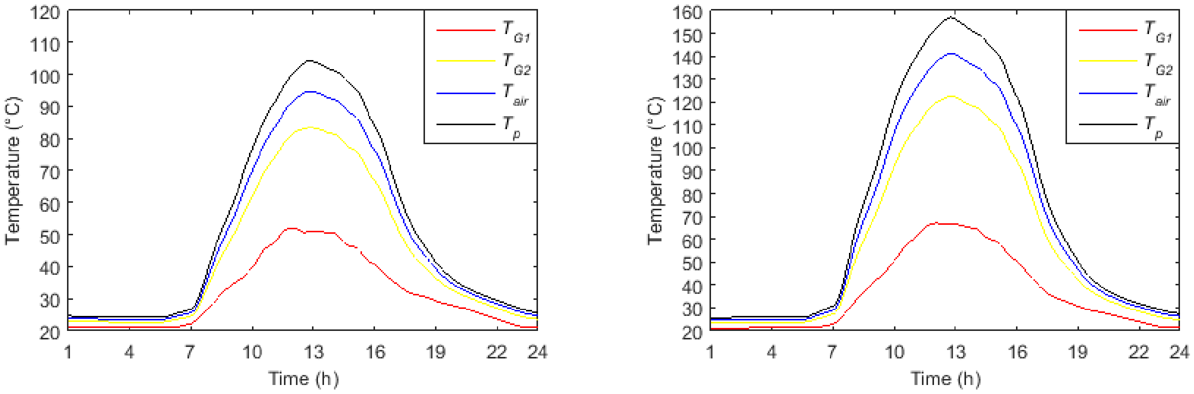
where V is the wind velocity.

4. Computer simulation

4.1. Numerical simulation based on finite differences method

An iterative MATLAB Program was developed to predict the temperature evolution relative to each component of the solar cooker. The most important temperature value to predict is the black aluminum plate temperature since the plate is in contact with the container. The adopted discretization method is the finite difference method. Simulations are realized for a solar cooker with and without outer reflectors to bring out the influence of the reflectors.

Fig. 3 illustrates the obtained results with the finite differences method for both of the configurations (with and without reflectors). The use of the outer reflectors is clearly benefit for the functioning since the aluminum plate temperature has increased from 104 °C to 158 °C. The availability as well has considerably increased to reach approximately 8 hours if a baking temperature of 100 °C is assumed.



a) b)

Fig. 3 Simulation results: Components temperatures
a) without outer reflectors b) with outer reflectors

4.2. Numerical simulation based on Solidworks Dynamic Thermal Simulation

To validate the accuracy of the proposed model, a numerical simulation using the Solidworks Dynamic Thermal Simulation was realized with the same ambient conditions used in the finite differences method implemented in the MATLAB program.

Fig. 4 shows the simulation workspace as well as the simulation tree and the placement of the boundary conditions. Simulations were carried out for the solar cooker with and without outer reflectors.

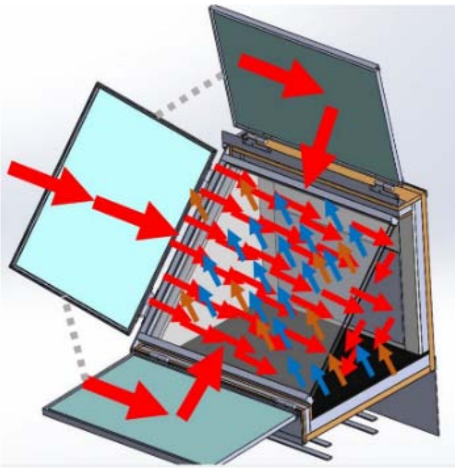
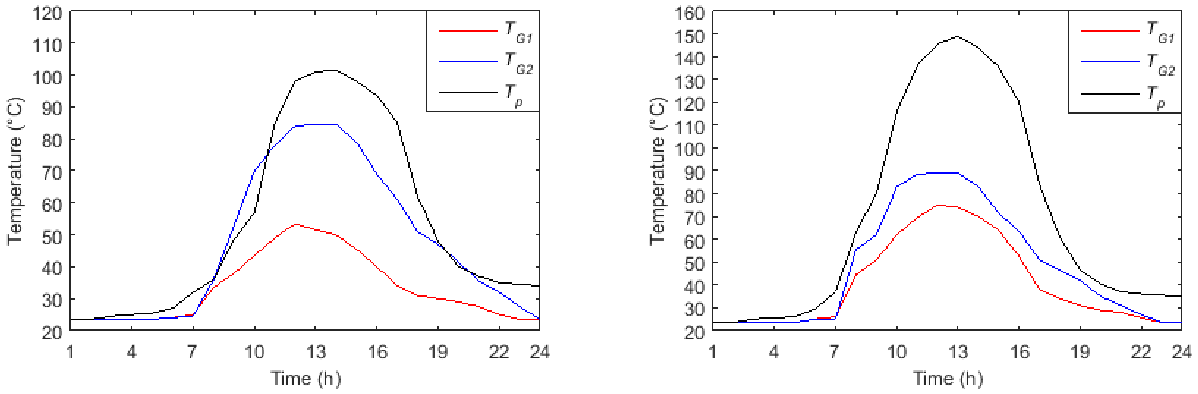


Fig. 4 Solidworks simulation work space



a) b)

Fig. 5Solidworks Thermal Simulation results: Components temperatures a) without outer reflectors b) with outer reflectors

The obtained results in Figure.5 are very satisfactory since the maximum error of the aluminum plate temperature does not exceed 2 % when the solar cooker is simulated without outer reflectors and 6.7 % when the solar cooker is simulated with outer reflectors.

6. Conclusion

This work consists on designing a box type solar cooker which is enhanced with an inner reflector and four outer reflectors. In addition, a detailed description of the mathematical model is developed. This modelling is used to predict the evolution of the main components temperatures for both cooker configurations (i.e. with and without outer reflectors). The mathematical model was numerically simulated and verified using a MATLAB program and Solidworks Thermal Simulation Tool. The obtained results show that the black aluminum plate temperature is close to 104 °C when the cooker is simulated without outer reflectors and close to 158 °C when the cooker is simulated with the outer reflectors. This result is very satisfactory since it brings out the benefit of the enhancement on the cooker performances. In addition, the use of the outer reflectors permits an availability that can reach 8 hours per day under the precise operating conditions.

References

[1] A. Gaur, O.P. Singh, S.K. Singh and G.N. Pandey, Performance Study of Solar Cooker with Modified Utensil, Renewable Energy, Vol. 18, N°1, pp. 121 – 129, 1999.

[2] A.V. Narasimha Rao and S. Subramanyam, Solar Cookers – Part II- Cooking Vessel with Central Annular Cavity, Solar Energy, Vol. 78, N°1, pp. 19 – 22, 2005.

[3] A. Harmim, M. Boukar and M. Amar, Experimental Study of a Double Exposure Solar Cooker with Finned Cooking Vessel, Solar Energy, Vol. 82, N°4, pp. 287 – 289, 2008.

[4] A. Soria-Verdugo, Experimental analysis and simulation of the performance of a box-type solar cooker, Energy for Sustainable Development, Vol 29, pp. 65-71,2015.

[5] A. Harmim, M. Merzouk, M. Boukar, M. Amar, Performance study of a box-type solar cooker employing an asymmetric compound parabolic concentrator, Energy, Vol 47, Issue 1, pp. 471-480, 2012.

[6] A. Regattieri, F.Piana, M.Bortolini, M.Gamberi, E. Ferrari, Innovative portable solar cooker using the packaging waste of humanitarian supplies, Renewable and Sustainable Energy Reviews, Vol. 57, pp. 319-326, 2016.

[7] L. Adelard, F. Pignolet-Tardan, T. Mara, P. Lauret, F. Garde, H. Boyer, Renewable energy energy efficiency, policy and environment sky temperature modelisation and applications in building simulation, Renewable Energy Vol 15,N°1,pp. 418 – 430,1998.